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Wind Pressures and Suctions on Roofs

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Although the dangers of damage to roofs from hurricane winds are vaguely appreciated by most people, the nature and distribution of wind forces are not generally understood. The subject is complicated and some understanding of air flow around buildings is required as a basis for sound roof design. It is the purpose of this Digest to assist the reader in acquiring this understanding.

By looking at the most striking effects of wind on roofs — damage caused by very high winds — three lessons can be learned.

1. Entire roofs are often lifted off a building: wind must exert strong lifting forces rather than pressures on roofs.
2. Damage is frequently confined to small sections near corners and ridges: the distribution of wind forces must be non-uniform, with extremes in certain areas.
3. Damage is sometimes limited to the roof covering proper — shingles or built-up roofing — rather than to the roof assembly as a whole: a pressure differential must exist across the roofing membrane alone rather than across the assembly.

Positive wind pressure, in the sense of a downward roof load, is almost never the cause of a failure. Even if there are occasional downward wind loads, roofs in Canada are normally well designed to carry downward loads from snow.

Structural damage from very strong (and fortunately relatively rare) winds is the most obvious effect of wind on roofs, but even moderate winds are important in the over-all picture. The movement of air through roof spaces must also be considered. The same wind-induced pressure distributions that cause structural loading also cause air to flow, even at moderate wind speeds, from regions of higher to regions of lower pressure if openings exist either intentionally or accidentally. The wind factor must, therefore, be taken into account in planning the size and location of ventilation openings. A difference may be, of course, that at low wind speeds building pressurization by mechanical equipment and, in winter, chimney effect can cause pressure differentials of the same order of magnitude as those produced by wind. In principle, however, it is best to put exhausts in areas of continuous suction (independent of wind direction).

Pressure Distribution on Roofs

It should be noted that although the magnitudes of the pressures and suctions are proportional to the square of the wind speed, the distribution of pressures and suctions does not change with speed for most "sharp-edged" structures and buildings. The pressure distributions can readily be expressed independent of wind speed by dividing the wind-induced pressures by the "stagnation pressure", $\frac{1}{2} \rho v^2$, where ρ is the air density and v is the wind speed.

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The stagnation pressure represents the total kinetic energy of the wind and is used as the basic design pressure. It is the pressure obtained on a surface perpendicular to the wind that makes the wind "stagnate" completely. To obtain the actual wind pressures or suctions on a surface the stagnation pressure is multiplied by pressure coefficients or shape factors appropriate to any given building surface. Pressures and suctions are measured relative to the barometric pressure of the undisturbed flow, which is given the value zero. Although the pressure distribution is far from uniform, average pressure coefficients for entire roof and wall surfaces are used to simplify the design problem.

Pressure coefficients for particular building shapes such as those contained in Supplement No. 3 to the National Building Code have been derived from wind tunnel tests on small-scale models. Meteorological data are naturally also required to supply the necessary design wind speeds for a specific geographical location. Finally, site investigations are sometimes desirable to allow an assessment of the probable sheltering or funnelling effects of neighbouring structures on the building to be designed.

Roof design for wind effects, then, appears to be a formidable task requiring the collaboration of three different specialists. Although it is true that the designer would be poorly equipped without the help of technical data, he is still responsible for applying information to arrive at the design of the roof. Sometimes what he needs is unavailable or only obtainable through *ad hoc* wind tunnel tests, but in any case the designer's task will be much easier if he has a good basic understanding of how pressure distributions are formed on buildings, and when and where to expect potentially serious conditions.

Basic Ideas

Figure 1 illustrates the simplest case of a "sharp-edged" obstruction to air flow over the ground. The obstruction is an infinitely long wall so that the flow is two-dimensional. The wall changes the momentum of the flow by pushing the streamlines upwards, and this creates a positive pressure on the wall. In Figure 1 there is a triangular vortex region in front of the wall in which the "trapped air" is under

positive pressure compared with the pressure in the undisturbed flow.

The streamlines, in addition to showing the direction of flow, indicate changes in speed; the closer they are crowded together, the greater is the speed at the section because the same amount of fluid must pass between two streamlines at any section. The pressure at any point in streamlined flow can be computed from the speed because the total energy, which is the sum of velocity energy and pressure energy, is constant.

The mathematical relations between velocities from point to point and the constancy of total energy can be applied to give the pressure distribution only if the flow is divided into a streamline zone and a turbulent zone containing the obstruction. If the obstruction were itself streamlined in shape, the streamlines could follow its surfaces and vortex regions would not form.

The shape of the boundary separating the vortex regions from the streamlined flow must be known before velocities and pressures can be calculated, although in fact the exact shape is usually not known. In practice, pressure distributions on sharp-edged shapes are found by experiment on scale models in a wind tunnel rather than by mathematical analysis. These ideas have been presented, not to enable one to compute pressure distributions, but to give a qualitative picture of wind flow around buildings that will help the understanding of pressure distributions found from wind tunnel tests.

One final hint in applying these basic ideas will be useful in visualizing where pressures and suctions occur: wherever the boundary of streamline flow is pushed up, pressure occurs; and wherever it curves back, suction occurs. The sharper the curvature of the boundary, the greater the pressure or suction will be.

Application of Basic Ideas

Despite the actual shape of the obstruction to flow (a right-angled projection into the flow path), it may be seen in Figure 1 that the streamlines are deformed just as if the obstruction were shaped like a smooth hump. The deficiencies of "streamlining" are made up by the formation of a positive vortex region in front and a larger, negative vortex region behind.



Figure 1 Wind flow over a long wall.

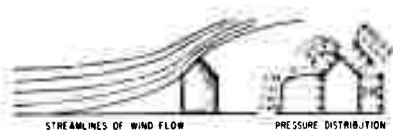


Figure 2 Two-dimensional wind flow over a building (after Jensen).



Figure 3 Separation at eave causing high suction (after Jensen).



Figure 4 Plan view of roof with negative pressure distribution shown by contour lines (after Leuthesser).

Figure 2 shows a complete building (still in two-dimensional flow) in which the roof is steep enough to protrude into the flow boundary formed by the front wall alone. This causes the streamlined flow to be pushed up even further, so that pressure occurs on the windward slope. If the slope of the roof is reduced, a point will be reached at which pressure on the windward slope becomes zero; if it is reduced further, the flow boundary will at first be sucked down and will continue to flow along the slope, and a change from pressure to suction will occur. As the slope is reduced even further, high local suction will develop near the eave, and a third vortex region, highly negative, will suddenly form, as is shown in Figure 3.

At a critical slope angle, maximum suction occurs; with further reduction there will be an easing of the suction, when the small vortex will merge with the larger "wake" of the building. The whole roof is then completely immersed in a region of fairly uniform, moderate suction, and further changes in the slope or shape within that region will not greatly affect the pressures.

Adding the Third Dimension

In three dimensions the streamline flow is diverted around the sides as well as over the top, with separation at sharp edges and the possibility of re-attachment to the side walls at certain orientations of the wind. The important parameters in determining the shape of the flow are the ratios of height to width and width to length of the building. For example, the critical roof slope for maximum roof suction (flow at right angles to the eaves) on a building 100 feet wide and 250 feet long is 5 degrees for a height of 12 feet, 20 degrees for a height of 100 feet, and 30 degrees for a height of 200 feet.

The greatest local suction occurs, especially with long, low-slope roofs, near the windward corner when the wind blows at an angle of 45 to 50 degrees to the eave. This is shown in plan view on Figure 4, where the lines of equal pressure are plotted as contours. Peak suction up to -4.0 times the stagnation pressure of the wind may occur close to a corner, because a strong negative vortex is formed at the corner as the flow curves up and over the two windward walls and separates at the sharp edge. When the roof is long, the flow can be

sucked back down to re-attach itself to the roof surface, so that the vortex region is effectively sealed off on all sides, preventing any reverse flow along the roof to relieve the high suction.

Parapets

Simple roofs without parapets or overhangs have so far been considered in this Digest. Such roof elements, however, have a considerable effect on pressure distribution. Recent model tests at the University of Toronto show that parapets can help to reduce the high local suctions just described. If it is of the proper height, a parapet can lift the flow and the separation lines high enough to prevent their re-attachment to the roof surface, so that one large vortex region forms to "absorb" the small, tightly sealed one.

If the parapet is too low, on the other hand, the local suctions can be even worse. An empirical formula has been derived from model tests at the University of Toronto that enables the parapet wall height to be chosen as a function of the dimensions of the building. For example, a building 50 feet wide, 100 feet long, and 25 feet high needs a parapet wall 5 feet high to reduce local suction maxima from -3.3 to -1.2 .

Internal Pressures

The internal pressure of the building has been tacitly assumed equal to the barometric pressure in the undisturbed flow, the reference datum or "zero" pressure. This will be true, however, only if the building is tightly sealed or if the distribution of "leaks" is fairly uniform, with the right proportion in pressure regions and suction regions. If openings predominate in a suction region, the internal pressure will tend toward suction, and if the openings are mostly on the windward side, the internal pressure will be positive.

The importance of internal pressure, whether positive or negative, to the resultant uplift forces on the roof is apparent. To take an extreme case, an airport hangar with huge

doors open on the windward side receives the positive pressure of the front vortex region under the roof. This adds to the external suction to cause uplift. With the wind coming from the opposite direction the effect is reversed. Thus wind from all directions must be considered in design, although obviously the critical case for uplift is with pressure inside. One should be clear as to which element of the roof is actually experiencing the pressure differential. If the air-tight element is not also the load-bearing element, trouble may arise.

Conclusion

It has been the aim of this Digest to present the basic ideas of wind effects on roofs in such a way that detailed discussions and the implications of the relevant factors can be readily appreciated by the designer. Wind loads in Canada, except for tornadoes, do not present especially difficult problems for the successful design of roofs, but the basic nature of the phenomenon must be understood. It should also be recalled that even when the wind is not blowing strongly enough to cause serious structural loads, suctions and pressures exist that may seriously affect the operation of a roof system, exhaust fan outlets, ventilators and the like. In all these situations there is nothing to replace a sound understanding of what actually happens when the wind blows around a building.

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